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An Automatic Segmentation of Bone Tunnels After Anterior Cruciate Ligament Reconstruction in MDCT Image Using K-means Clustering

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Abstract

The anterior cruciate ligament (ACL) reconstruction is usually performed for the injured knee. The ACL reconstruction needs two bone tunnels. It is important to measure changing of the bone tunnel regions after surgery. Thus this study aims to propose an automated segmentation about anteromedial (AM) and posterolateral (PL) parts of the bone tunnels after double bundle ACL reconstruction using k-means clustering. Six patients were evaluated (Age 27 ± 7 , four males / two females). As a result, this method could be divided for all patients. This study concluded that the proposed method is enough to divide the bone tunnels of double bundle technique after ACL reconstruction.

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Keywords: ACL reconstruction, MDCT image, bone tunnel ;

1. Introduction

The anterior cruciate ligament (ACL) is a ligament which connects the femur and tibia, and plays a role of preventing an excessive anterior translation of the tibia during knee bending [1]. The ACL injury is a common ligament injury of the knee joint [2], and happens with high frequency among accidents of active sports (i.e., football, soccer, basketball, handball, skiing, etc.). The ACL injury can cause a reason to increase instability along anterior - posterior translation at extension [3]. The injured ACL knee has a risk for secondary injury (i.e., meniscal lesion, chondral disruption, osteophytosis, synovium hyperplasia, etc.) [4]. Therefore, operative treatment is preferred rather than conservative treatment when instability of daily life is high for an active

young person or a person with multiple ligament injuries [5, 6], because a self-reparation of the ACL is rare due to its low healing ability.

The ACL reconstruction has increasingly focused on the anatomical double bundle technique more than single bundle technique. The single bundle technique reconstructs the ACL by using one harvested graft. Double bundle technique reconstructs separately the anteromedial (AM) and posterolateral (PL) bundles at the center of the anatomical attachment of the AM and PL bundles [7]. The harvested graft passes the bone tunnels for connecting the femur and tibia. Then, fixation devices fix the grafts.

In recent years, the ACL has become one of the most frequently studied structures in the musculoskeletal system. Currently, 75,000 - 100,000 ACL reconstructions are estimated annually in only the United States [8, 9]. However, it has been reported that a range from 10 % to 25 % of these patients may experience pain, graft failure, and recurrent instability [10-12]. Postoperative widening of the tibial and the femoral tunnel, which is visible on radiological images, is one of the causes that has been identified. Among the related complications, tunnel enlargement has been reported in recent years regardless of the used technique [13].

The bone tunnel enlargement can potentially complicate an ACL revision procedure [14]. Revision surgery involves staged reconstruction and additional surgical procedures and entails significant costs. Wide tunnels also alter the direction of the graft within a joint. Not only requiring a second surgery, but being the potential for additional giving-way episodes further risks injury to the menisci and articular cartilage. Bone tunnel enlargement occurs over time, not immediately after surgery [15]. Several authors found that tunnel enlargement occurred early (0 - 3 months) and stabilized within a year [16]. Others have observed tunnel enlargement to progress up to 2 years after surgery [17].

The mechanism of bone tunnel enlargement following ACL reconstruction is not yet clearly understood [18]. The possible causes such as mechanical and biological factors have been considered. The mechanical factors include graft tunnel motion, stress ablation of bone within the tunnel wall, improper graft tunnel placement, and aggressive rehabilitation [19]. The biological factors include a cytokine-mediated nonspecific inflammatory response, cell necrosis due to toxic products (ethylene oxide, metal), a foreign body (allograft) immune response, and heat necrosis as a response to drilling.[20].

Studies have measured the diameter of the bone tunnel using CT and MRI images in double bundle ACL reconstruction. Although studies have evaluated the size of the bone tunnel after double bundle ACL reconstruction using CT and MRI images, those results may be not accuracy, because those methods cannot evaluate the segmentation of the bone tunnel [21]. It is important to evaluate size of the bone tunnel with double bundle ACL reconstruction. No study reports to segment AM and PL of the bone tunnel after the double bundle ACL reconstruction. A purpose of our study is to propose an automated segmentation about AM and PL of the bone tunnels after double bundle ACL reconstruction.

2. Methods

The measurement method consists of three steps (Fig. 1). The first step preprocesses to divide the region of AM and PL in the bone tunnel. The second step divides the bone tunnel into AM and PL by k-means. The final step evaluates the tunnel volumes of AM and PL.

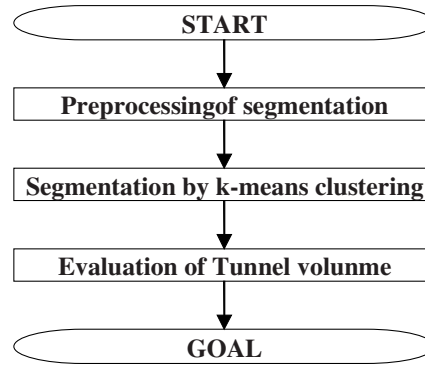


Fig. 1. Procedure of the proposed method.

2.1. Preprocessing of segmentation

A preprocessing of segmentation has three advantages. First, a k-means method needs to locate a first gravity point from initial segmented region of the bone tunnel. Second, a volume of initial segmented region decreases an error to segment the bone tunnel by k-means method. Third, this method decreases a calculation time to segment the bone tunnel accurately.

Fig. 2 shows preprocessing to segment AM and PL of the bone tunnels. This method consists of five steps. This method applies the principal component analysis (PCA) to segmentation of the bone tunnel regions. The PCA computes the first principal component vector \mathbf{V}_1 and second principal component vector \mathbf{V}_2 . This method computes four points (\mathbf{A} , \mathbf{P} , \mathbf{A}' , \mathbf{P}') as farthest location from the center of gravity \mathbf{G} . Contour points \mathbf{A} , \mathbf{P} , \mathbf{A}' , and \mathbf{P}' are calculated from

$$\begin{cases} IP_1(i) = \mathbf{V}_1 \cdot \mathbf{GI}(i) \\ IP_2(i) = \mathbf{V}_2 \cdot \mathbf{GI}(i) \end{cases} \quad (1)$$

$$\begin{cases} \mathbf{A} = \arg \max_{\|\mathbf{GI}(i)\|} \mathbf{I}(i) \text{ (if } IP_1(i) < 0 \text{ and } IP_2(i) < 0) \\ \mathbf{P} = \arg \max_{\|\mathbf{GI}(i)\|} \mathbf{I}(i) \text{ (if } IP_1(i) < 0 \text{ and } IP_2(i) > 0) \\ \mathbf{A}' = \arg \max_{\|\mathbf{GI}(i)\|} \mathbf{I}(i) \text{ (if } IP_1(i) > 0 \text{ and } IP_2(i) < 0) \\ \mathbf{P}' = \arg \max_{\|\mathbf{GI}(i)\|} \mathbf{I}(i) \text{ (if } IP_1(i) > 0 \text{ and } IP_2(i) > 0) \end{cases} \quad (2)$$

where i is the number of voxel. $\mathbf{I}(i)$ is the object voxel. $\mathbf{GI}(i)$ is the vector from \mathbf{G} to $\mathbf{I}(i)$. $IP_1(i)$ and $IP_2(i)$ are the inner product of \mathbf{V}_1 and $\mathbf{GI}(i)$, and \mathbf{V}_2 and $\mathbf{GI}(i)$, respectively. This method computes the midpoint \mathbf{S} and \mathbf{D} between \mathbf{A} and \mathbf{P} , and \mathbf{A}' and \mathbf{P}' . \mathbf{S} and \mathbf{D} are calculated from

$$\begin{cases} \mathbf{S} = \frac{\mathbf{A} + \mathbf{P}}{2} \\ \mathbf{D} = \frac{\mathbf{A}' + \mathbf{P}'}{2} \end{cases} \quad (3)$$

This method computes the vectors **AP** and **SD**. **AP** and **SD** are calculated from.

$$\begin{cases} \mathbf{AP} = \mathbf{P} - \mathbf{A} \\ \mathbf{SD} = \mathbf{D} - \mathbf{S} \end{cases} \quad (4)$$

This method segments the temporary regions of AM and PL using **AP** and **SD**.

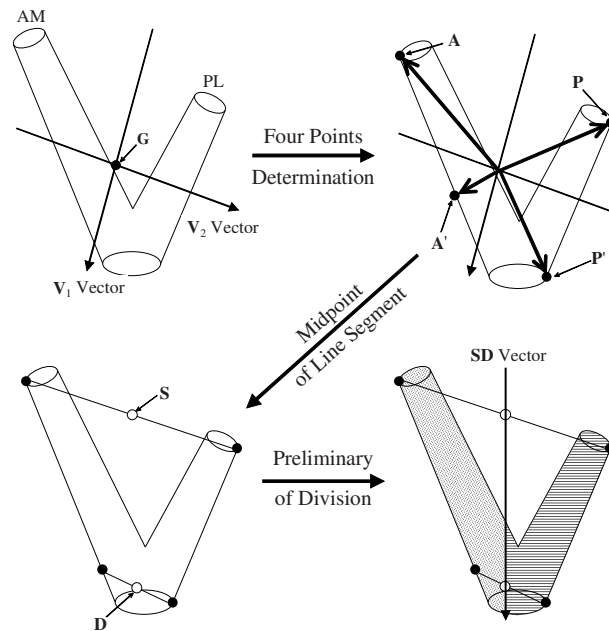


Fig. 2. Preprocess to segment AM and PL of the bone tunnels.

2.2. Segmentation by k-means clustering

A segmentation by k-means clustering has three advantages. First, the k-means clustering method provides quantitative and stable segments of the bone tunnel. Second, the k-means clustering method can automatically segment the bone tunnel. Third, the k-means clustering method decreases a calculation time to segment the bone tunnel in comparing with other methods. Fig. 3 shows an example to segment AM and PL of the bone tunnels by k-means clustering.

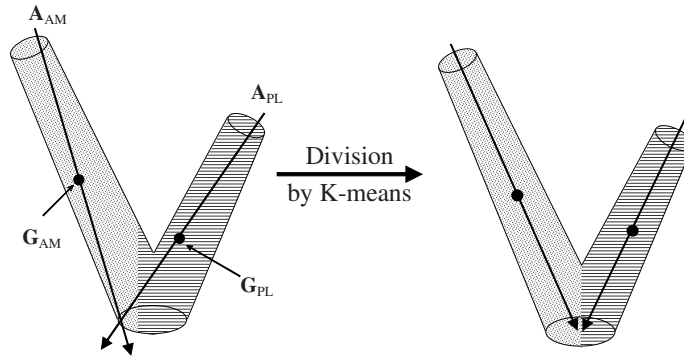


Fig. 3. Segmentation for AM and PL of the bone tunnels by k-means.

This method consists of three steps (Fig. 4). The first step computes the gravity point \mathbf{G}_{AM} and \mathbf{G}_{PL} from the temporary region of AM and PL. The second step calculates the long axes (first principal component axes) \mathbf{A}_{AM} and \mathbf{A}_{PL} by PCA. The third step segments the new region of AM and PL from \mathbf{G}_{AM} and \mathbf{G}_{PL} , and \mathbf{A}_{AM} and \mathbf{A}_{PL} by the k-means clustering. The new region $\mathbf{I}'(i)$ is calculated from

$$\begin{cases} d_{AM}(i) = \|\mathbf{A}_{AM} \times \mathbf{G}_{AM} \mathbf{I}(i)\| \\ d_{PL}(i) = \|\mathbf{A}_{PL} \times \mathbf{G}_{PL} \mathbf{I}(i)\| \end{cases} \quad (5)$$

$$\mathbf{I}'(i) = \begin{cases} \text{AM (if } d_{AM}(i) < d_{PL}(i)) \\ \text{PL (if } d_{AM}(i) > d_{PL}(i)) \end{cases} \quad (6)$$

where $d_{AM}(i)$ and $d_{PL}(i)$ are the shortest distance between \mathbf{A}_{AM} and $\mathbf{I}(i)$, and \mathbf{A}_{PL} and $\mathbf{I}(i)$, respectively. $\mathbf{G}_{AM} \mathbf{I}(i)$ and $\mathbf{G}_{PL} \mathbf{I}(i)$ are vectors from \mathbf{G}_{AM} and \mathbf{G}_{PL} to $\mathbf{I}(i)$, respectively. This method returns to the first step, and continues to the loop until the region of AM and PL converges (Fig. 4).

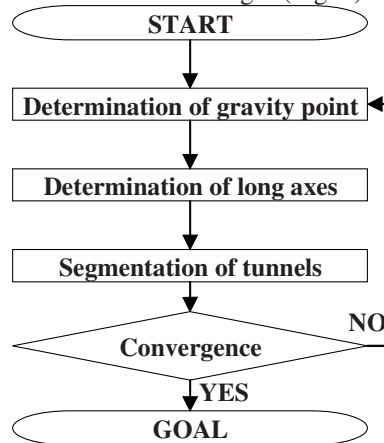


Fig. 4. Flowchart of segmentation by k-means clustering.

2.3. Evaluation of the tunnel volumes

Accuracy of the proposed method is verified by comparing the true value as a manual extraction. Evaluation value system of the proposed method, obtained from the matching rate of the extraction area of the proposed method and the manual method (true value). The matching rate v is calculated from

$$v = \frac{1}{2} \left(\frac{\iiint_{x,y,z} (m(x,y,z) \cdot a(x,y,z)) dx dy dz}{\iiint_{x,y,z} m(x,y,z) dx dy dz} + \frac{\iiint_{x,y,z} (m(x,y,z) \cdot a(x,y,z)) dx dy dz}{\iiint_{x,y,z} a(x,y,z) dx dy dz} \right) \quad (7)$$

where $\forall x \in [0, X]$, $\forall y \in [0, Y]$, and $\forall z \in [0, Z]$ are a position of an object voxel, are defined $X = 512$, $Y = 512$, and $Z = 200$ from the parameter of the MDCT images in this study. $m(x, y, z)$ and $a(x, y, z)$ are a extracted voxel by the manual method and proposed method, are binary images.

3. Experiments

Six patients were used (Age 27 ± 7 , four males / two females). This study consists of two experiments. The first experiment validates the quantization error of this method. The second experiment compares the segmentation precision of the proposed method with the manual method (Fig. 5). This experiment segmented the bone tunnels tilted the different angle (0° , 10° , 20° , and 30°) by the manual and this method, compared to the matching rate of 0° and 10° , 0° and 20° , 0° and 30° . The results of this experiment are the average of each matching rate.

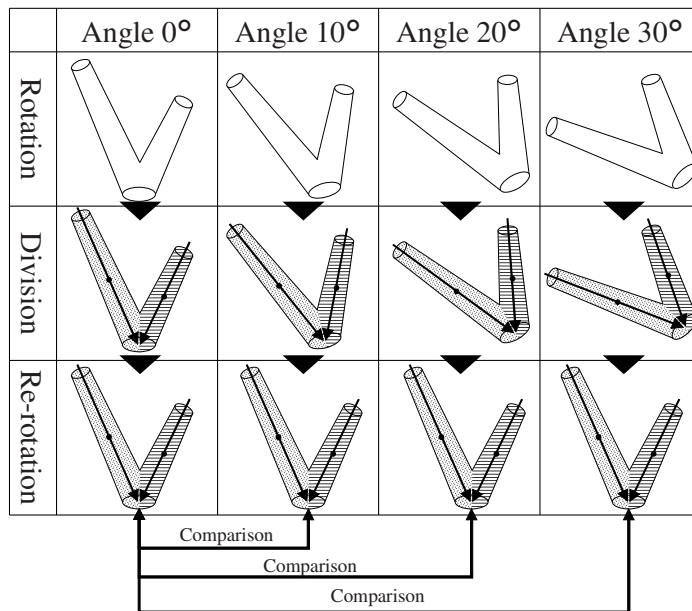


Fig. 5. Experiment of comparison of different angle.

4. Results

Table 1 shows the results of the simulation experiment. The femur and tibia of "All" were $98.98 \pm 0.35 \%$, $98.85 \pm 0.39 \%$, respectively. Table 2 shows the results of the clinical experiment. AM and PL of the femur and tibia of "Manual Method" were $98.61 \pm 0.69 \%$, $98.24 \pm 0.97 \%$, $96.16 \pm 0.86 \%$, and $95.58 \pm 0.83 \%$, respectively. AM and PL of the femur and tibia of "Proposed Method" were $98.92 \pm 0.35 \%$, $98.74 \pm 0.33 \%$, $98.29 \pm 0.42 \%$, and $98.30 \pm 0.37 \%$, respectively. Fig. 6 shows examples of divided image of the bone tunnels.

Table 1. The results of the matching rate for the all region of bone tunnels of "All"

| | Average | S.D. |
|-------|---------|------|
| Femur | 98.98 | 0.35 |
| Tibia | 98.85 | 0.39 |

The unit of "Femur" and "Tibia" are %.

Table 2. The results of the matching rate for the manual and method region of bone tunnels

| | | Manual Method | | Proposed Method | |
|-------|----|---------------|------|-----------------|------|
| | | Average | S.D. | Average | S.D. |
| Femur | AM | 98.61 | 0.69 | 98.92 | 0.35 |
| | PL | 98.24 | 0.97 | 98.74 | 0.33 |
| Tibia | AM | 96.16 | 0.86 | 98.29 | 0.42 |
| | PL | 95.58 | 0.83 | 98.30 | 0.37 |

The unit of "Femur" and "Tibia" are %.

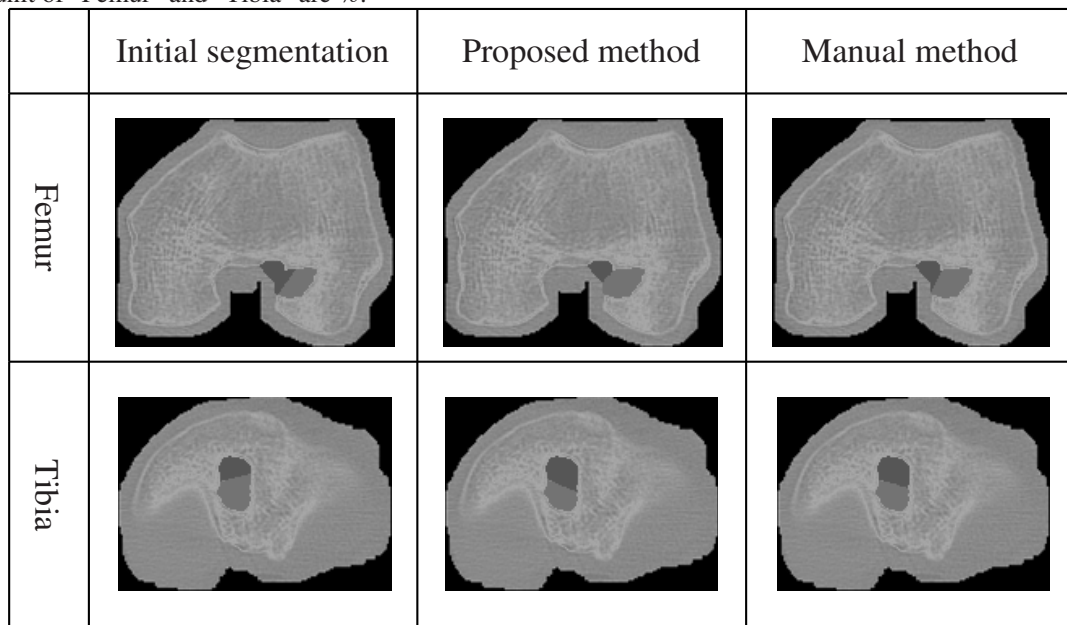


Fig. 6. Examples of divided image of the bone tunnels.

5. Discussion

The first experiment validated the quantization error of this method. Table I shows that the errors of affine transform were 1.02 % (femur) and 1.15 % (tibia). Since the quantization error of this method is small, this experiment validated the quantization error of this method. The second experiment compared the segmentation precision of the manual method with proposed method (Table 2). Since all the matching rate is larger than 95 %, this experiment validated the precision of this method. Since the matching rates of this proposed method were larger than the manual method, this proposed method is more precisely than the manual method. The matching rates of the tibia were larger than the femur, because of the overlapping region of AM and PL in tibia is larger than femur. Fig. 6 shows that this method was able to segment the bone tunnels to AM and PL regions. Because this proposed method could accurately segment the bone tunnels, it can contribute to evaluate the size of the bone tunnels of double bundle technique after ACL reconstruction.

This proposed method has three advantages. The first advantage is to segment bone tunnels independently from the angle. The second advantage is full automatic and fast processing. This analysis can be executed less than 30 seconds with PC (Intel(R), Core(TM), i7 CPU, 920 @ 2.67 GHz, 9.99 GM RAM). The third advantage is to evaluate bone tunnels more accurately than manual method, because the matching rates of this proposed method were larger than the manual method (Table II).

This study proposed a segmentation method of the bone tunnels of double bundle technique after ACL reconstruction. In the results, the first experiment (Table I) validated that the quantization error was small, and the second experiment (Table II) was able to validate the correctness of this method. This study concluded that the proposed method is enough to divide the bone tunnels of double bundle technique after ACL reconstruction.

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